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MEMORANDUM REPORT ARBRL-MR-03115

BLAST COMPUTATIONS OVER A HEMICYLINDRICAL AIRCRAFT SHELTER

John D. Wortman

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July 1981

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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HULL-Experiment Comparisons
LAMB

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a three dimensional, finite difference hydrocode (HULL) simulation of an experiment for blast leakage into a hardened aircraft shelter model. The computer program uses LAMB subroutines to simulate the blast wave and HULL to solve the hydrodynamic equations. Experimental and computed pressure-time results are compared. Some additional HULL results are shown and advantages and difficulties are discussed.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

I. INTRODUCTION

Necessity or expediency sometimes forces stockpiles of explosive munitions to be stored in the vicinity of highly vulnerable targets such as aircraft. Often one takes measures to protect the aircraft by housing them in various hangar-like buildings. This protection permits more efficient use of space by allowing a higher aircraft storage density. A particular kind of aircraft storage shelter used in Europe is one that is hemicylindrical in shape with doors that slide sideways at the ends (Quonset hut shape). In an effort to quantify the measure of protection afforded aircraft, BRL has undertaken the task of measuring the blast environment that parked aircraft would experience when a munitions detonation occurs nearby. The experimental portion of the task was performed by Kingery[1] and measurements at various locations inside and outside the shelter model are reported for a number of different door openings and shock obliquity impingements.

This report describes a complementary computational effort on the same problem. It serves as a difficult test for the HULL[2,3] hydrocode in a further attempt to validate its predictive capability for three dimensional problems. Previous computations with HULL proved extremely fruitful. Shock impingements of various strengths and obliquities on an S-280 Electronic Equipment Shelter model are discussed in References 4, 5, and 6. Comparisons with shock tube experiments on the model show very good agreement. Similar computations were performed for shock

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1 *Kingery, C.N., "Blast Leakage Into a Hardened Aircraft Shelter Model", (to be published as a BRL Report), U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.*

2 *Fry, M.A., Durrett, R.E., Ganong, G.P., Matuska, D.A., Stucker, M.D., Chambers, B.S., Needham, C.E., and Westmoreland, C.D., "The HULL Hydro-dynamics Computer Code", AFWL-TR-76-183, U.S. Air Force Weapons Laboratory, Kirtland Air Force Base, NM (September 1976).*

3 *Hasdal, J.A., Chambers, B.S., Clemens, R.W., "Support to BRL: HULL Code Implementation on a CDC 7600", SAI-80-701-AQ, Science Applications Inc., McLean, VA (August 1979).*

4 *Lottero, R.E., "Comparison of 3-D Hydrocode Computations for Shock Diffraction Loading on an S-280 Electrical Equipment Shelter", ARO Report 80-3, Proceedings of the 1980 Army Numerical Analysis and Computers Conference (August 1980).*

5 *Lottero, R.E., "Detailed Comparison of 3-D Hydrocode Computation for Shock Diffraction Loading on an S-280 Electrical Equipment Shelter", (to be published as a BRL Report), U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.*

6 *Lottero, R.E., Wortman, J.D., Bertrand, B.P., and Kitchens, C.W., "Oblique Interaction of a Shock Wave with a Three-Dimensional Simple Structure, Part I", (to be published as a BRL Report), U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.*

impingements on open structures[7]. From the pressure differences between the outside and inside walls, one can draw conclusions as to vulnerability of the structure. In all these problems the shock input was of the constant pressure (step shock) type. The present computation uses LAMB[8], a code based on a standard 1 KT nuclear blast[9], to generate a decaying blast wave to simulate the wave generated in the experiment. Pressure-time results are compared at the various measuring stations in the floor of the model and regions of focused (high) pressure are correlated and pointed out.

II. COMPUTATIONAL PROCEDURE

A. Test Model

In order to convey the ideas for the computational model, a brief description of the test performed on the scale model is given here. The experiments are described more completely in Reference 1.

The test structure is a 1/42 scale model of a U.S. third generation semi-hardened aircraft shelter. There were several different experimental configurations. The computation in this report compares with the particular conditions depicted in Figure 1. For this test, there are two models: Model A with its longitudinal axis aligned with the charge burst point and its partially open end facing the burst, and Model B at an angle of 90° to the burst. The computational simulation is concerned only with Model A. The test models were 87.1 cm long sections of pipe with an inside diameter of 57.4 cm that had floors welded somewhat above the center. The resulting inside dimensions were 54.8 cm across the floor and 20.09 cm high. These models were buried so the floors were level with the ground. The front of Model A had a centered slot opening from the roof to the floor that was 30% of the front (presented) cross-sectional area of 809.3 cm^2. Ten pressure gauges were located on the floor as indicated in Figure 2. There were also two free field pressure gauges, labeled F1 and F2, located 183 cm and 289 cm from ground zero, respectively (see Figure 1). A charge of .758 kg of TNT was used to produce a nominal 103 kPa (15 psi) blast wave at 289 cm (the distance from ground zero to gauge F2 and the inside center of the front wall of Model A). This scaled charge-distance relationship represents 56,181 kg of TNT at a distance of 121.5 m.

7 *Wortman, J.D., Kitchens, C.W., and Lottero, R.E., "Prediction of 3-D Blast Loading on a Partially Open Industrial Building: Feasibility Study", (to be published as a BRL Memorandum Report), U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.*

8 *C.E. Needham and L.A. Wittwer, "The Air Force Weapons Laboratory Low Altitude Multiple Burst (LAMB) Model", AFWL-DYT-75-2 (unpublished).*

9 *Needham, C.E., Havens, M.L., and Knauth, C.S., "Nuclear Blast Standard (1 KT)", AFWL-TR-73-55 (Rev.) U.S. Air Force Weapons Lab., Kirtland Air Force Base, NM (April 1975).*

B. Computational Grid and Boundary Conditions

HULL grid cells are parallelepiped shaped only. Although this is a drawback when attempting to model complicated geometry, many structures of interest to the Army can be represented with reasonable computational accuracy. The original intent for this project was to carry out the computation with a coarse grid and then repeat the computation with a finer mesh. The assignment of the grid was complicated by the need to follow the curvature of the roof, have the proper cross-sectional area, and have a slot door opening that was 30% of this area. The cells in the region of interest, the aircraft shelter model and immediate vicinity, were all about 3 cm by 2 cm by 3 cm. This was smaller than we originally intended, but the smallest cell face was still about five times larger than the gauge faces. However, in view of the relatively good comparison between the computations and the experiment, it was felt that a recomputation with smaller cells was not warranted at this time. We took advantage of symmetry to cut the modeled region in half. The computational region is sketched in Figure 1. Figure 3 shows a sketch of the front of the computational shelter model showing the end of the stair step representation for the curved roof and the closed and open portions of the front.

The faces of cells within the shelter and nearby had a 3 to 2 aspect ratio. This increased gradually with distance from the shelter. The 65 mesh spaces in the x direction diminished from 8.998 cm at x = 0 to 3.03 cm at the shelter model and gradually increased beyond the shelter model to 10.394 cm at x = 289 cm. The 31 mesh spaces in the y direction varied from 2.03 cm at y = 0 (the model center) to 32.842 cm at y = 243 cm. The 32 mesh spaces in the z direction varied from 2.85 cm at z = 0 (the model floor) to 35.394 cm at z = 243 cm. The resulting grid contained 64,480 cells.

The boundaries were placed to allow at least 3.5 milliseconds between shock arrival at the shelter and the arrival of any spurious signal from the boundaries. (This time was based on the crude assumption that all signals traveled at the shock velocity.) For example, when the reflected shock from the aircraft shelter reaches the LAMB input boundary at x = 0 the computation at this boundary becomes meaningless. Spurious waves are then propagated back toward the shelter. To a lesser extent the interaction between the shock wave and the transmissive boundaries (the x boundary at 289 cm and the y and z boundaries at 243 cm) produce a similar false reflection. All the outer boundaries were treated as transmissive which in HULL is an extrapolative scheme where boundary cells are given the same values as their inside neighbors. The bottom boundary at z = 0 and the boundary at y = 0 were treated as perfectly reflective. The one cell thick walls of the shelter model were designated ISLAND cells, which are also totally reflective. The LAMB input boundary at x = 0 was simulated with a virtual external row of cells that were assigned hydrodynamic values specified by LAMB as functions of time and location.

A 1.2767×10^{-6} KT burst was assumed at the external point (x,y,z) = (-144.5,0,0). This yield was chosen so that LAMB calculations would match the experimental free field gauge peak overpressure of 97.5 kPa at 2.89 meters from the burst point.

The HULL calculations were initiated at time = 2.455 ms with the shock front about 2 cells in front of the shelter. Initial hydrodynamic values at, and behind, the shock wave were supplied by LAMB. Ambient values were inserted in front of the shock to simulate undisturbed air. Then the HULL calculations proceeded with LAMB values using input through the x = 0 boundary.

III. RESULTS

The main purpose of this work was to make quantitative comparisons between experiments and HULL computations. As a necessary byproduct a decaying wave capability was introduced into HULL to simulate a three dimensional free field blast (see the APPENDIX). Overpressures were recorded as functions of time in the experimental series at the ten labeled locations in Figure 2. These were all on the floor of the model. These experimental pressure records are compared with HULL predictions in Figures 4a through 4j. The zero time for each experimental plot is the time of arrival of the shock wave at the transducer location. Since the experiment and the HULL calculation did not have the same reference time, a time shift for the HULL results was selected by matching the points of inflection on the leading edge of the pressure-time histories at Position 1 (see Figure 2) just inside the open door. This time shift of -0.63 ms in the HULL results was applied to each computed waveform inside the shelter.

A. Overpressures Inside the Shelter

In general, the computed HULL overpressures match the experimental records fairly well, although the computed values do not exhibit the high frequency response evident in the experiments. There are at least two reasons for this: First, the transducers in the experiment exhibit some noise (ringing) and it is sometimes difficult to differentiate the true pressure peaks from noise peaks. Second, the computational cell size is larger than the sensitive area of a typical transducer; this causes an "average" value to be computed and thus rounds the peaks.

The comparison at gauge A-1 (Figure 4a) near the narrow door is the poorest. The peak pressure of 104 kPa recorded here at 291 cm from ground zero is higher than the 97.5 kPa recorded with the free field gauge at 289 cm from ground zero. However, it is difficult to tell whether the peak of 104 kPa is a true peak or noise. If it were noise, the average value approximates 97.5 kPa more closely. On the other hand, we could be seeing the effects of reflections within the door opening itself in which case the multiple peaks would be real. Finally, it is not known to what extent viscous effects, which HULL ignores, influence the flow in the narrow opening.

The experiment recorded a significantly higher peak pressure at gauge A-8 than at A-9 which is in the center of the building near the back wall (see Figures 4i and 4j, respectively), where HULL recorded nearly equal pressures. This is because the experimental model had a small opening in the back near the center gauge and this opening was omitted from the computer model.

The highest computed overpressure inside the model was 97.6 kPa in the back corner near the floor. This points to a problem of shock focusing and should be brought to the attention of the shelter user.

We include examples of HULL generated plots for computed overpressure at two additional stations. Figure 5a shows the overpressure in a cell on the ground, in front of the building, at the center of the opening. This shows the strong reflected shock from the front of the building and later the reflected shock through the opening from the back of the model. Figure 5b shows the overpressure in the back corner of the model where HULL predicted a high pressure.

B Free Field Overpressures

Two HULL sampling stations were located 289 cm from ground zero, the same distance as free field gauge F-2. Both of these were in large cells. One station was in a cell about 3.5 by 13 by 3 centimeters on a side (cells inside the shelter model were about 3 by 2 by 3 cm). Its center was 289.7 cm from ground zero and the radial distance across it was about 7.8 cm. The second station was in a larger cell, 6.5 by 27 by 3 cm. Its center was 283.4 cm from ground zero and the radial distance across it was nearly 24 cm. This latter cell was more than half engulfed in the shock wave at the start of the computation. In Figure 6 the overpressure records from these two cells are superposed over the experimental record from free field gauge F-2. Beyond the initial peak, both HULL results are good approximations.

C. Isobars and Vector Plots

Although isobars generally indicate only qualitative results, they are instructive because they show the progression of shock waves, formation of vortices, and point to complex shock patterns such as Mach stems, triple points, etc. Figure 7 shows isobars at 5 ms in the bottom computation plane. Figure 8 shows isobars in the vertical plane adjacent to the $y = 0$ symmetry boundary at the same time. The walls of the model are outlined as a low contour value. The interpolation for this contour tends to thicken the apparent walls. The straight sections of the isobars near the transmissive boundaries is due to the large size of the cells and the extrapolation-type boundary condition used there. The scallops in the isobars are caused by interpolation between the centers of large cells.

Figures 9a through 9c show three isobar plots along the floor of the model. The high pressure region that forms and sweeps along the wall and floor is pointed out by the half-rounded contours in Figure 9a. This causes the sharp pressure spike in Figure 4f.

Velocity vector plots indicate the magnitude and direction of the moving gas. Figures 10a through 10c, with times corresponding to Figures 9a through 9c, clearly show a vortex generated just inside the door of the model.

The maximum pressures inside the model occur at the door when the shock front first enters and at the back wall when the shock front reflects from it at about 6 ms. The maximum velocities occur at the open door when the shock wave first enters, but high velocities are evident in the middle of the model in Figures 10a and 10b. A complete flow reversal, due to an inward traveling rarefaction wave, will cause debris and cargo stored inside the shelter to pile near the open door.

IV. COMMENTS AND CONCLUSIONS

It is evident that the HULL computations can be used to help plan further experiments, to aid in interpreting experimental results, and to fill gaps in experimental studies.

Except for the sharp peaks and valleys in the pressure records, the computed pressures in this study were a good approximation to the experimental pressures at most of the test locations. Such results would probably be quite adequate for structural response analyses. The rounding of the peaks in HULL is caused by the diffusion of the difference method and by the fact that HULL computes average values in each cell. Depending on time and expense, we could force HULL to define the peaks more sharply by using a finer mesh. In our present case we had cells of about 3 by 2 by 3 centimeters in the shelter region. The HULL run required about 1½ hours of the CDC 7600 CPU time to simulate 5.5 ms of real time. If we simply filled the same space with proportionally reduced cells so the smaller cells were cubes 1 cm on a side (this would approach the pressure gauge size) and repeated the run, it would take roughly 36 times as long for 18 times as many cells and half the time step. The resulting 54 hours of CDC 7600 computer time is prohibitive for most purposes. There are many factors which affect the rate at which HULL solves a problem. The present case averaged .32 ms per cell per cycle. (The time step for a cycle is one-half the smallest cell dimension divided by the shock velocity.)

HULL runs require a lot of personnel time. The present project took several man months with most of that time spent on code checking and modifications. Barring unforseen difficulties it is estimated that it would take two or three weeks to do a preliminary study (e.g.

LAMB runs to establish yield, initiation time, initial conditions, etc.) and set up the grid with proper boundaries, sampling stations, etc. for a similar computation for a different building. Actual running of the KEEL (program which sets up a HULL computation) and HULL codes does not take much personnel time, but the results, particularly from the KEEL run, should be checked at each stage. The most useful form of HULL output is obtained through plots. Analysis of these plots and correlation with experimental data is time consuming. Some time must also be devoted to the management of files. For this project the final restart file contained 19 restart dumps and over 6,000,000 words. This large amount of data must be manipulated carefully in order to properly interpret the computed results and to make comparisons with experimental pressure records.

ACKNOWLEDGMENT

The author would like to acknowledge the assistance of Andrew Mark for his many improvements to the content of this report.

APPENDIX A

HULL and LAMB.

The HULL[2,3] (Air Force Weapons Laboratory version 8) code used for this computation is an air blast version received at the BRL in September, 1978. It was modified by Science Applications Inc. under contract to the BRL[8] to run on the CDC 7600 at the BRL. Other changes by SAI and BRL personnel introduced the optional input of an oblique "step" shock and the replacement of the preprocessor SAIL[10] by a combination of the CDC utility UPDATE and the SAI program POST. These maintain and update files and select the particular coding for a given run. This collection of coding, which we loosely refer to as HULL, is a number of related programs and subroutines. The program of principal interest, called HULL, does the hydrodynamic calculations.

The program HULL is also really a collection of programs and subprograms. In particular, the three-dimensional (3-D) and two-dimensional (2-D) programs are different. The 2-D version is older. There are a number of options for the 2-D HULL version which are not in the 3-D version. The desired options for any run are selected through input control parameters. The results reported in this report are from the 3-D version and the changes and comments discussed apply only to the 3-D version.

The HULL hydrocode uses an explicit time-step scheme (in the spirit of Lax-Wendroff) to solve the inviscid Euler equations. This computation is carried out in two phases: first a Lagrangian calculation "steps" velocity and energy forward in time, and then an Eulerian transport phase computes the mass movement between cells and adjusts the energy and velocity accordingly. The hydrodynamic variables stored for each computational cell for 3-D runs are the three components of velocity, the specific internal energy, and the mass of material in the cell. The other hydrodynamic variables needed for the solution are density, total specific energy, pressure, and the "effective" gamma (ratio of specific heats of the gas). The average density in the cell is found from the mass and dimensions of the cell. The total specific energy is computed from the velocity and internal energy. The pressure and effective gamma are supplied by the equation of state.

The HULL program runs are preceded by a KEEL run which sets up the computational grid and the initial conditions. The computational grid consists of rectangular parallelepiped cells set off by orthogonal parallel planes. For 3-D runs, the contents of a cell is either AIR or ISLAND. Any region with non-ambient conditions is entered in a "geometry" (any of several geometric shapes can be specified). For each geometry containing AIR, the KEEL routine subdivides each cell into 27 equal subcells. If the center of a subcell is inside the

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10 *Graham, D.C., Gaby, L.P., and Rhoades, C.E., "SAIL, An Automated Approach to Software Development and Management", AFWL Interim Report 1971-6, U.S. Air Force Weapons Laboratory, Kirtland Air Force Base, NM, October 1976.*

specified geometric region specified hydrodynamic variables are assigned to one twenty-seventh of the cell. For geometries designated as ISLAND, the entire cell is designated ISLAND (a totally reflective cell) if the center of the cell is in the geometry. At the end, any unfilled portions of cells are filled with ambient air. During the HULL run, a hydrodynamic variable in a cell may be considered either the average value in the cell, the value in the cell, or the value at the center of the cell.

Positions called STATIONS, at which hydrodynamic data as a function of time are collected, are assigned in the KEEL run. Most of the variables and control parameters for HULL are also defined through KEEL.

The package of coding called LAMB (acronym for Low Altitude MultiBurst) is a collection of programs and subroutines which, among other things, can produce the hydrodynamic variables needed by HULL, for any position and time, from one or more bursts of nearly arbitrary yields and positions. There was optional coding in the HULL program to use part of the LAMB subroutines to supply hydrodynamic variables at some boundaries. We could not find coding in KEEL to initiate the grid directly from LAMB. We later modified KEEL to use LAMB subroutines, as in HULL, to supply initial values.

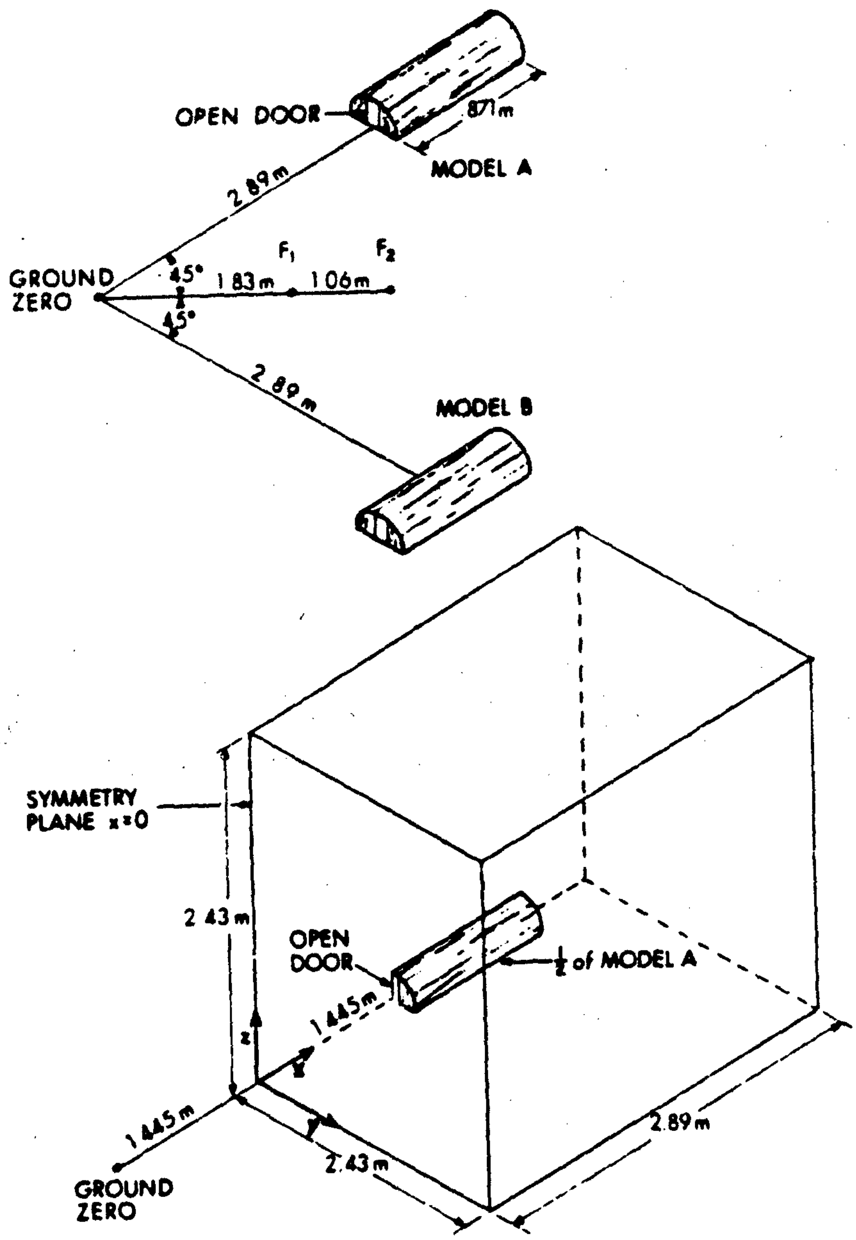

Figure 1. Sketch of the test set-up for which computation was performed.

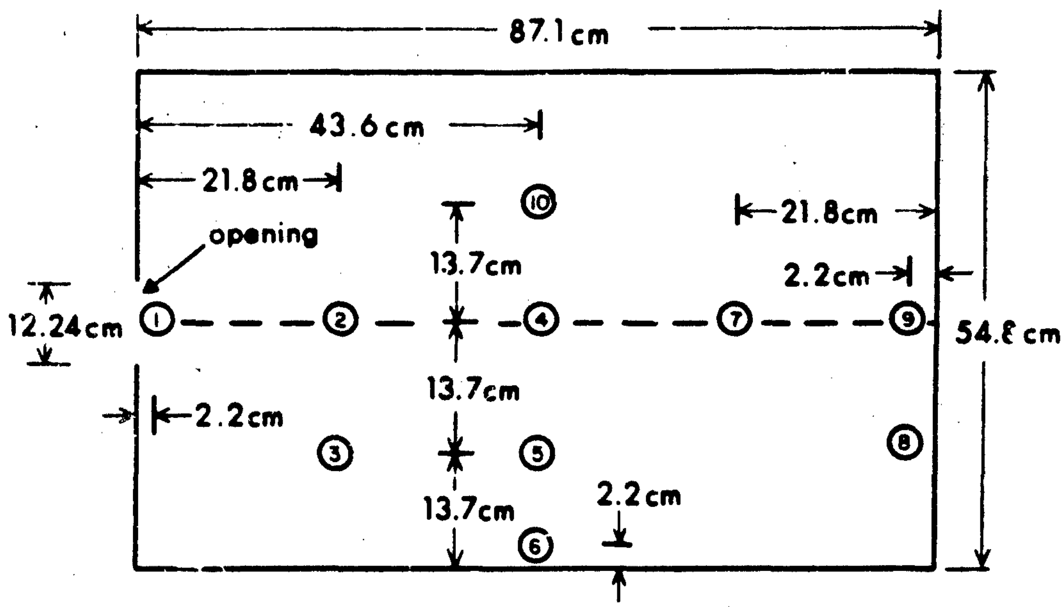

Figure 2. Schematic of pressure gauge locations for test.

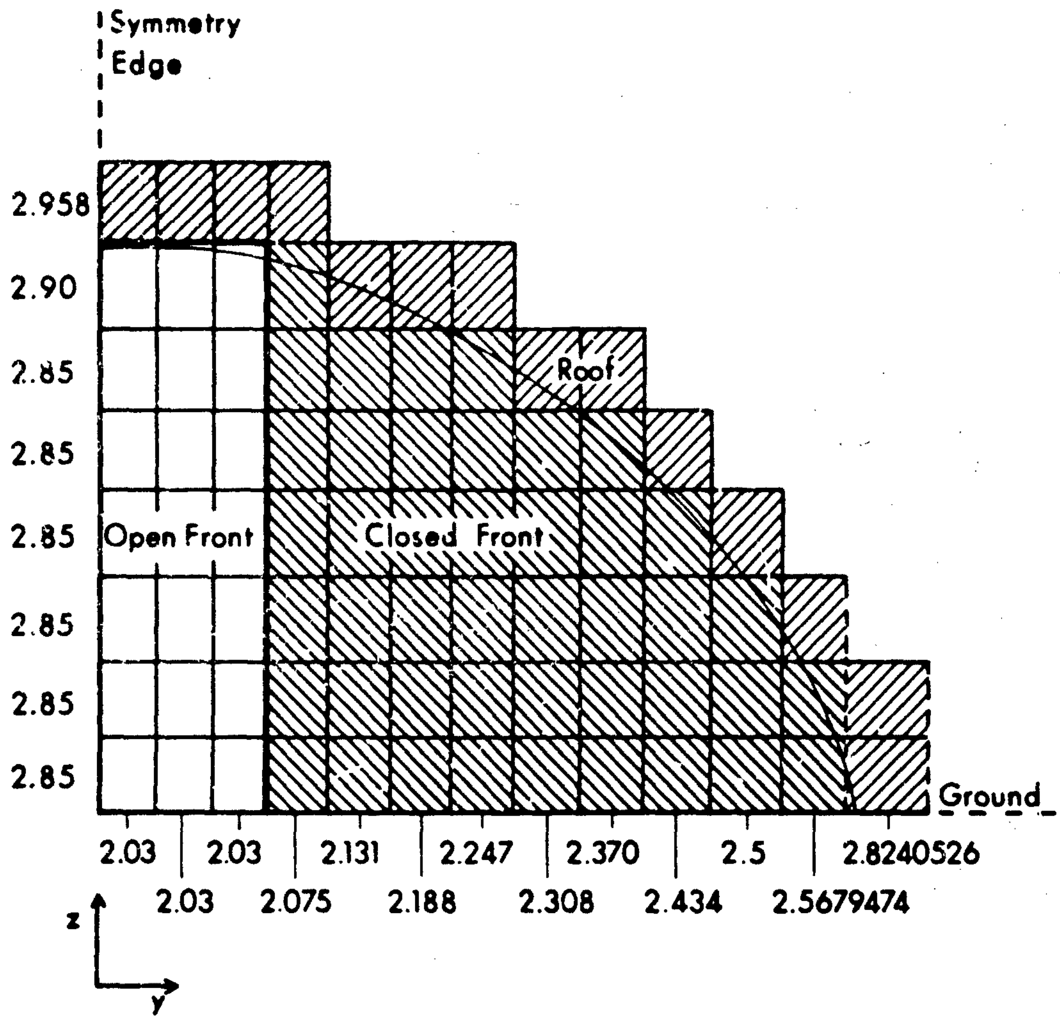

Figure 5. Computational grid on front of aircraft shelter model.

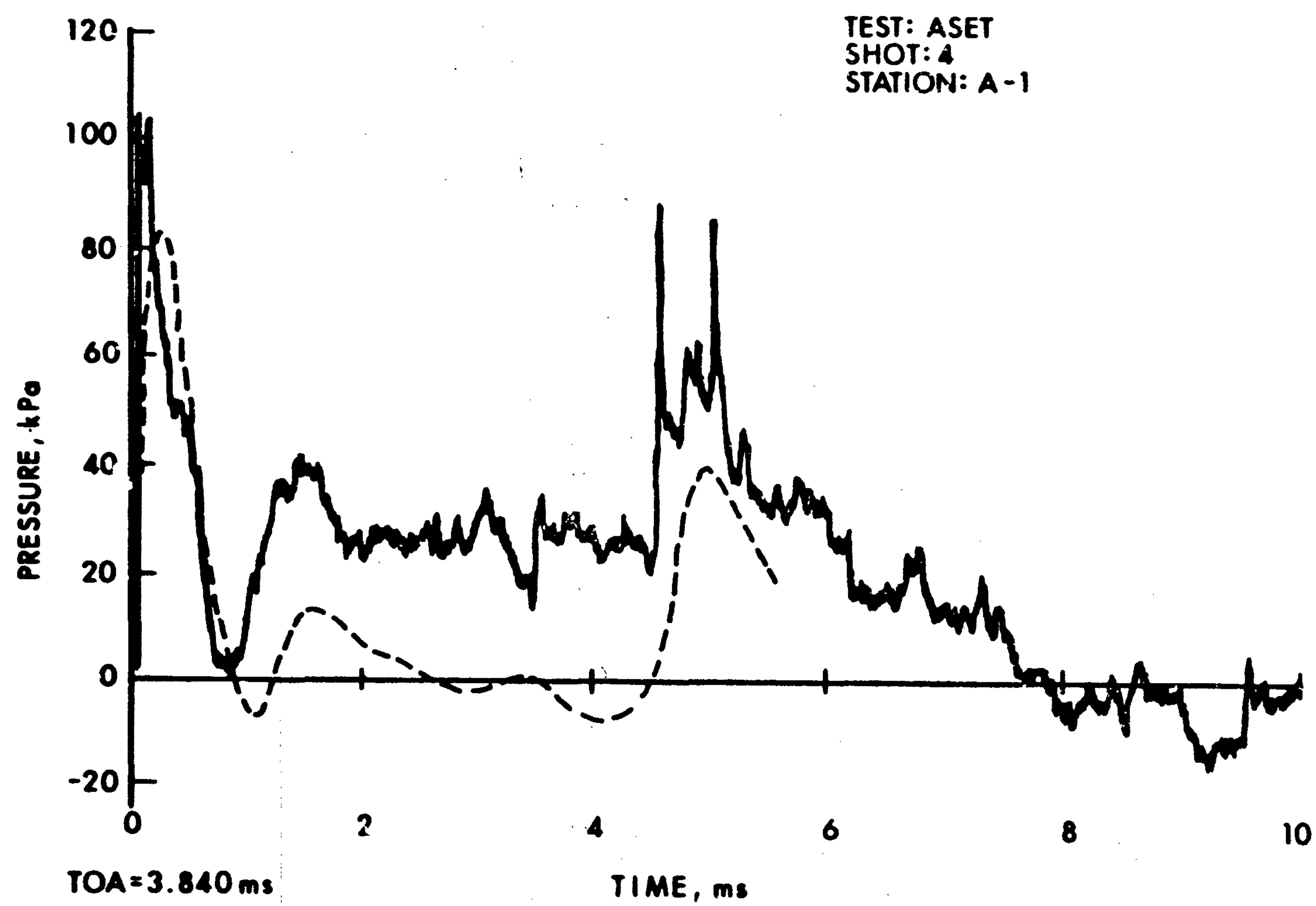

Figure 4a. Comparison of measured and HULL predicted overpressure at gauge position 1.

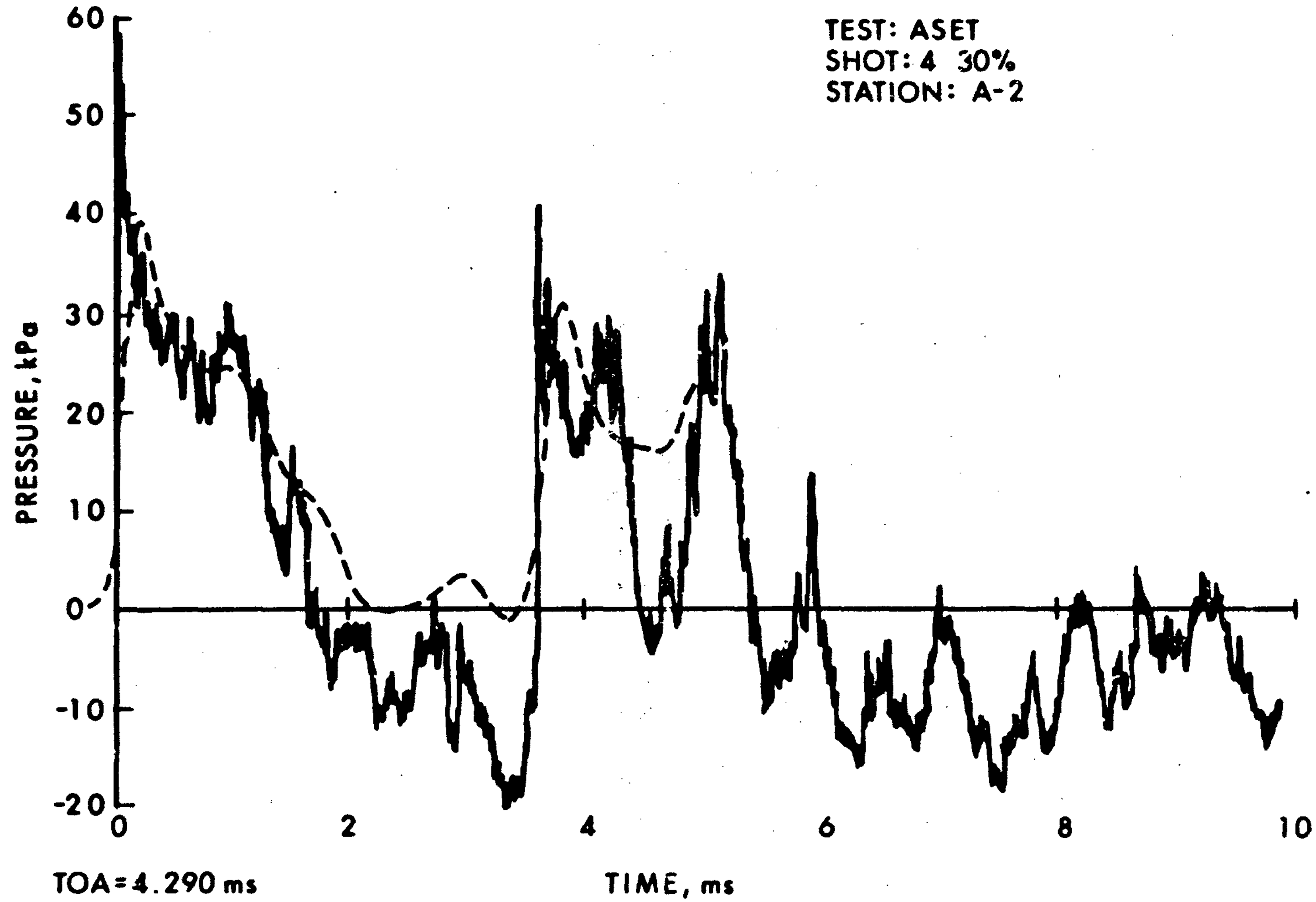

Figure 16. Comparison of measured and HULL predicted overpressure at gage position 2.

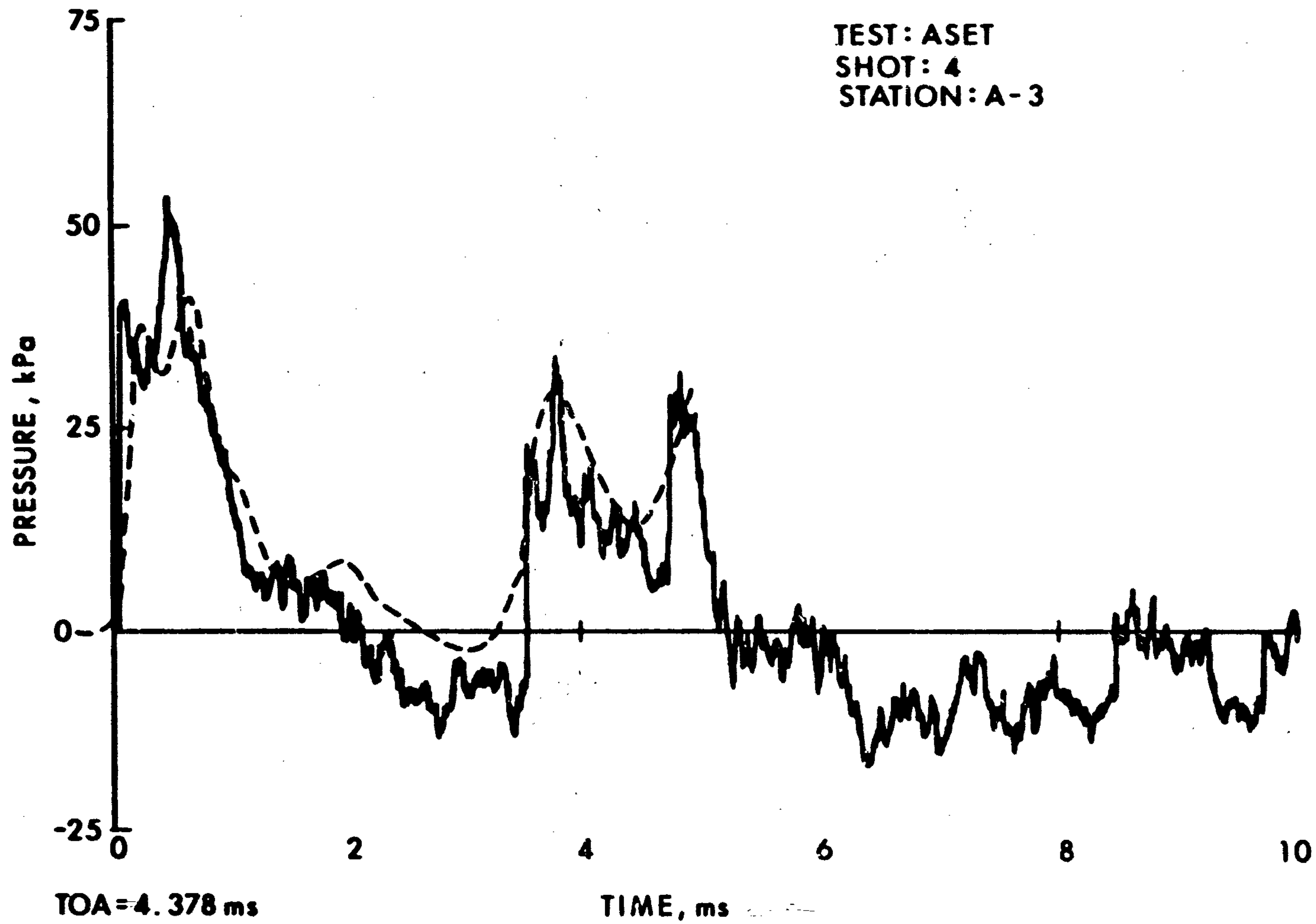

Figure 4c. Comparison of measured and HULL predicted overpressure at gauge position 3.

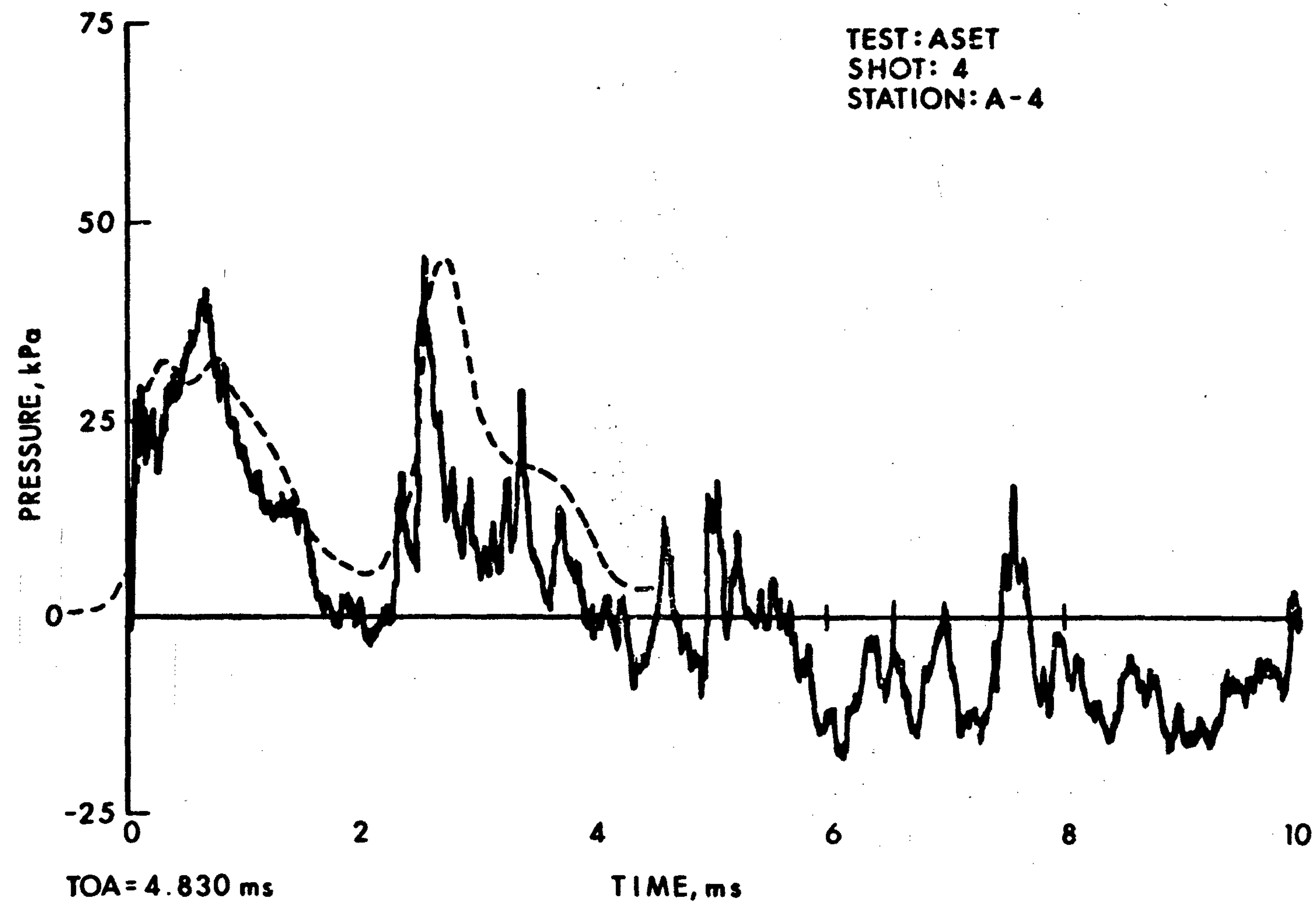

Figure 4d. Comparison of measured and HULL predicted overpressure at gauge position 1.

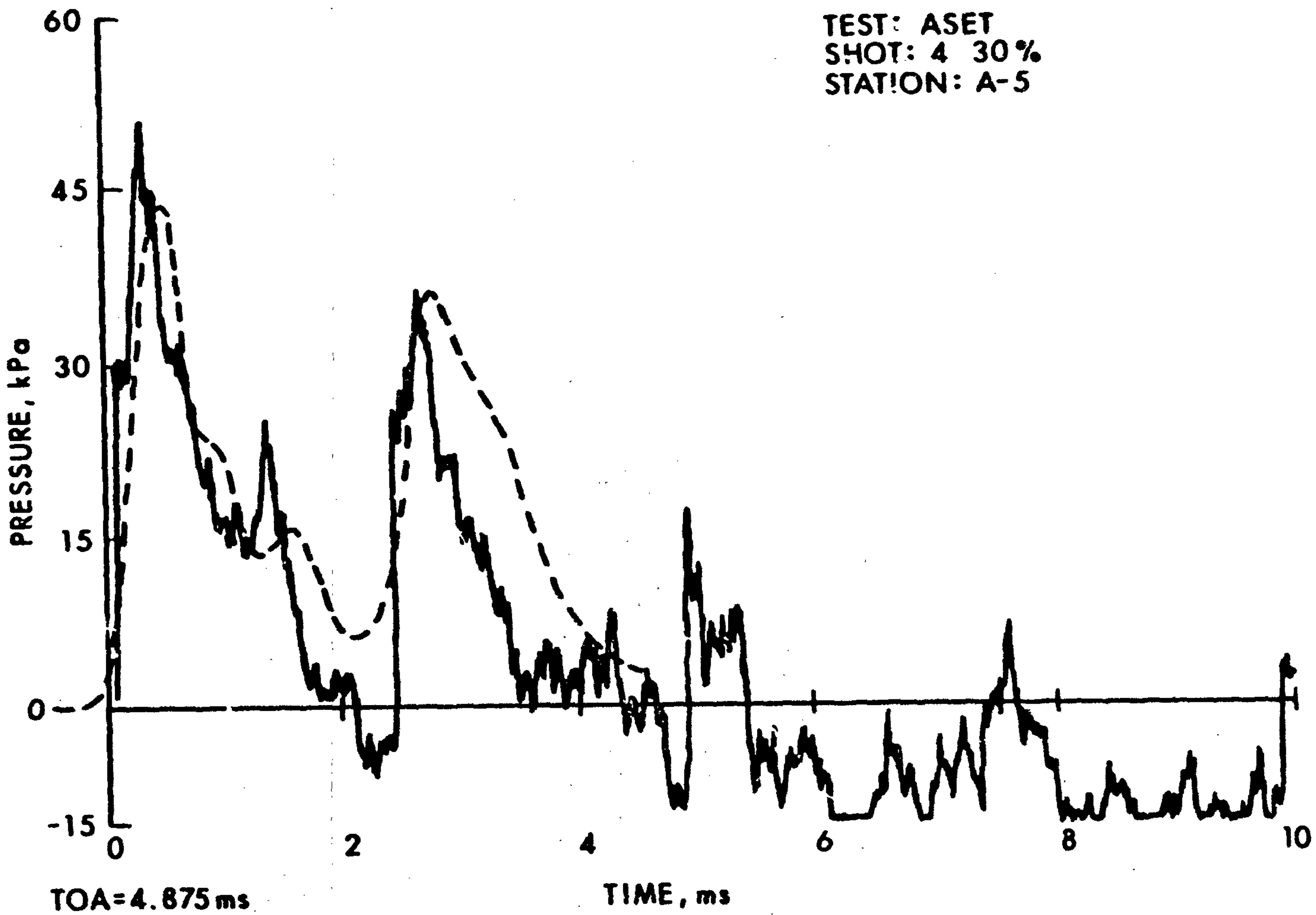

Figure 4e. Comparison of measured and HULL predicted overpressure at gauge position 5.

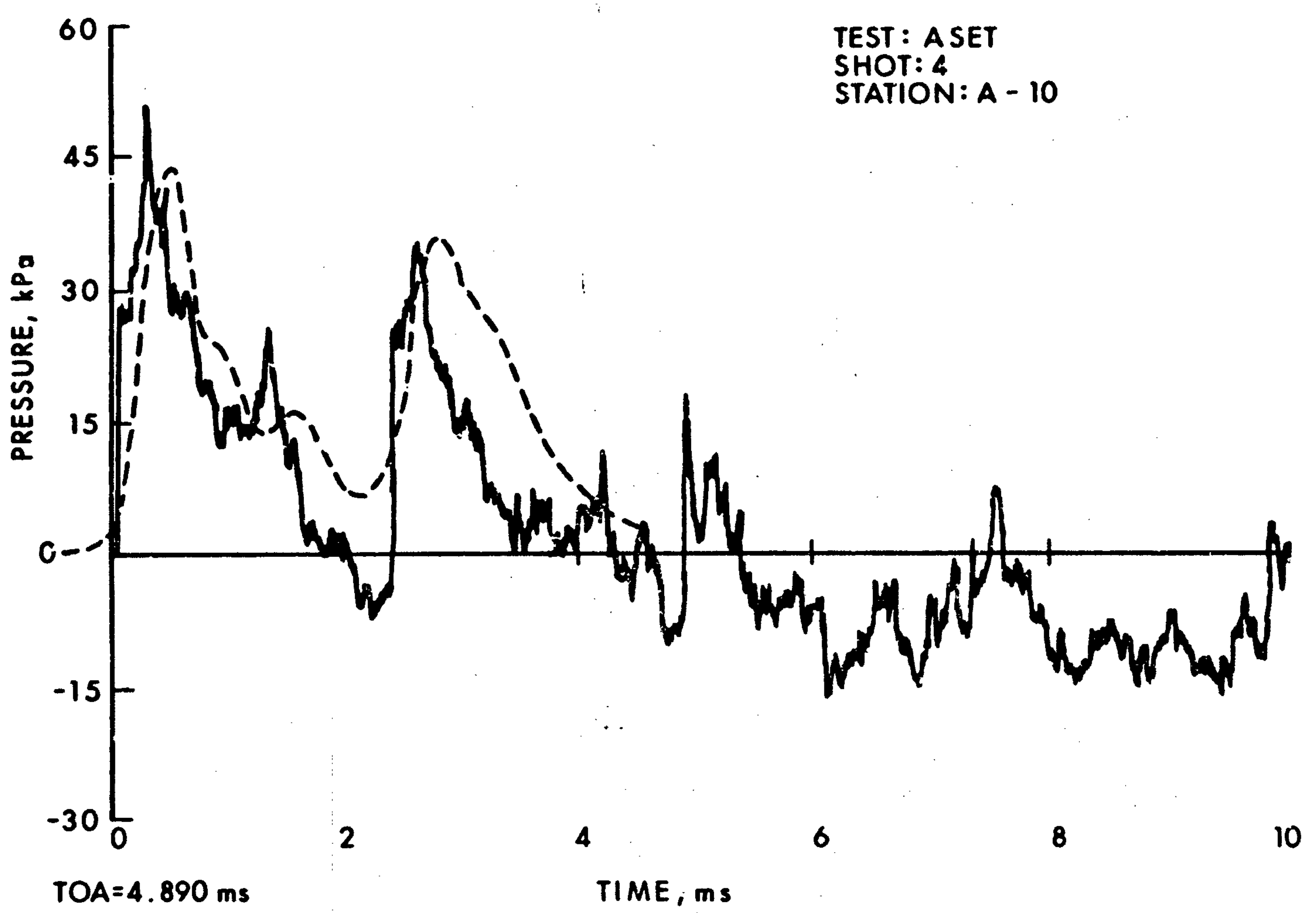

Figure 4f. Comparison of measured and HULL predicted overpressure at gauge position 10.

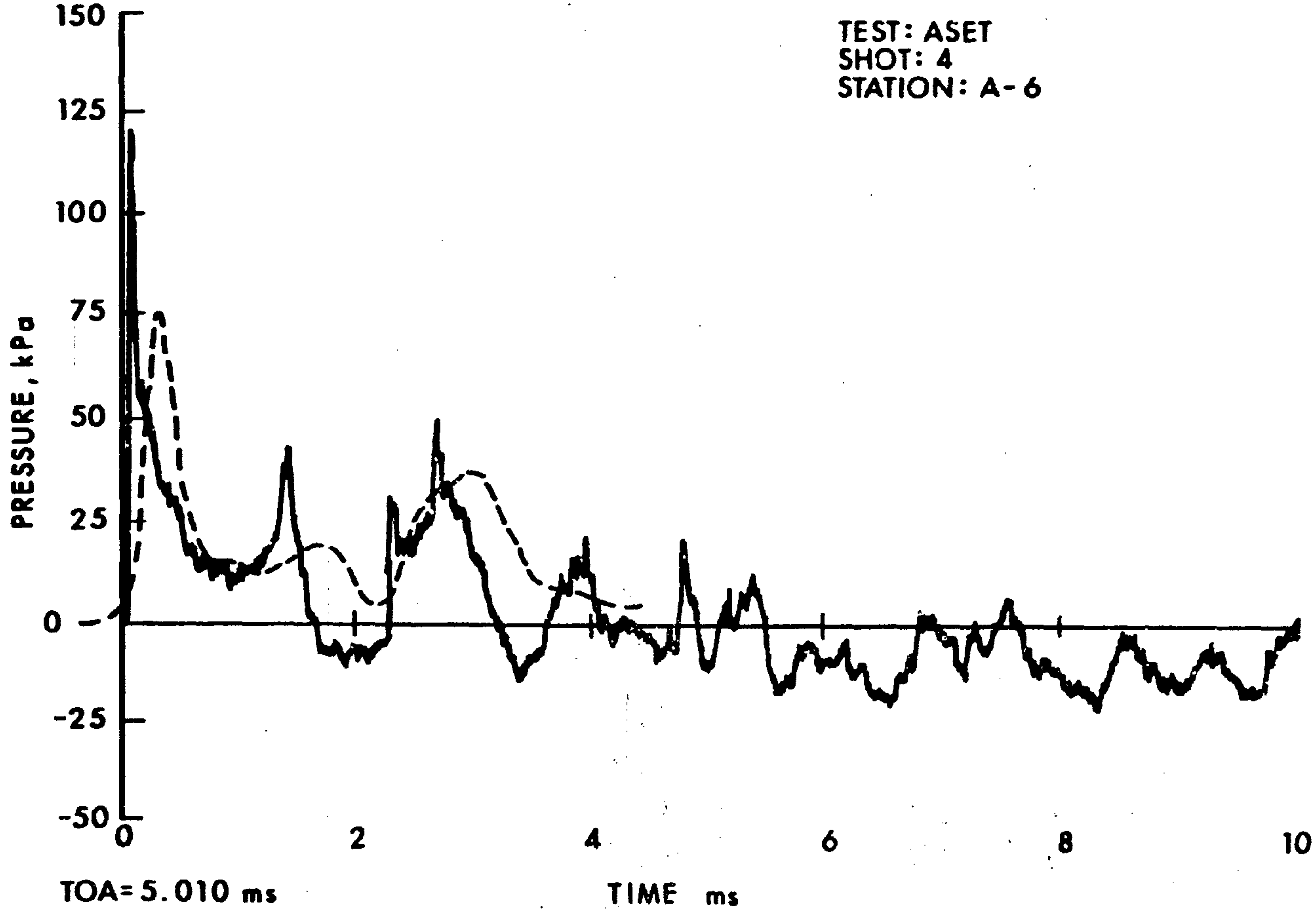

Figure 4g. Comparison of measured and HULL predicted overpressure at gauge position 6.

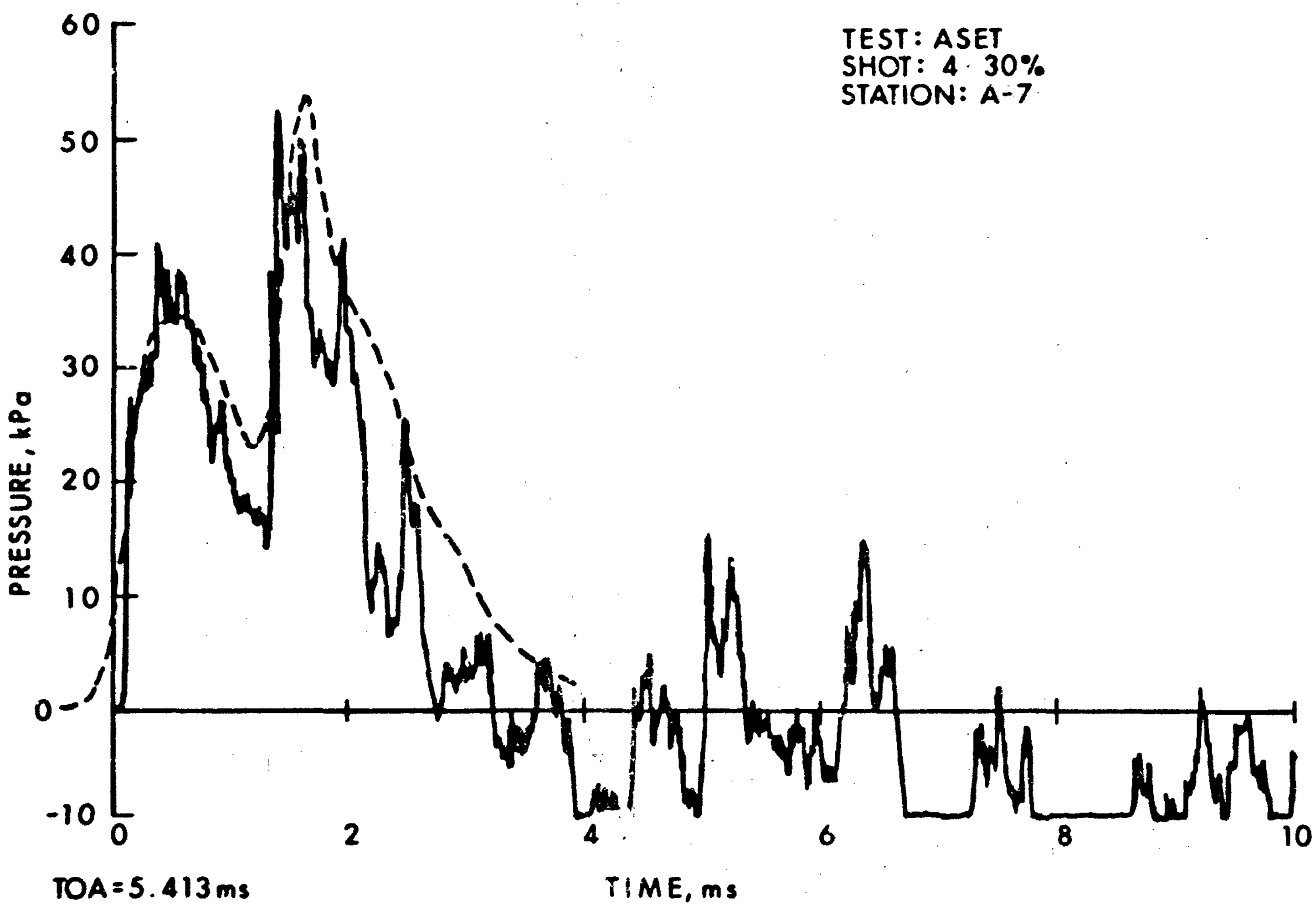

Figure 4h. Comparison of measured and HULL predicted overpressure at gauge position 7.

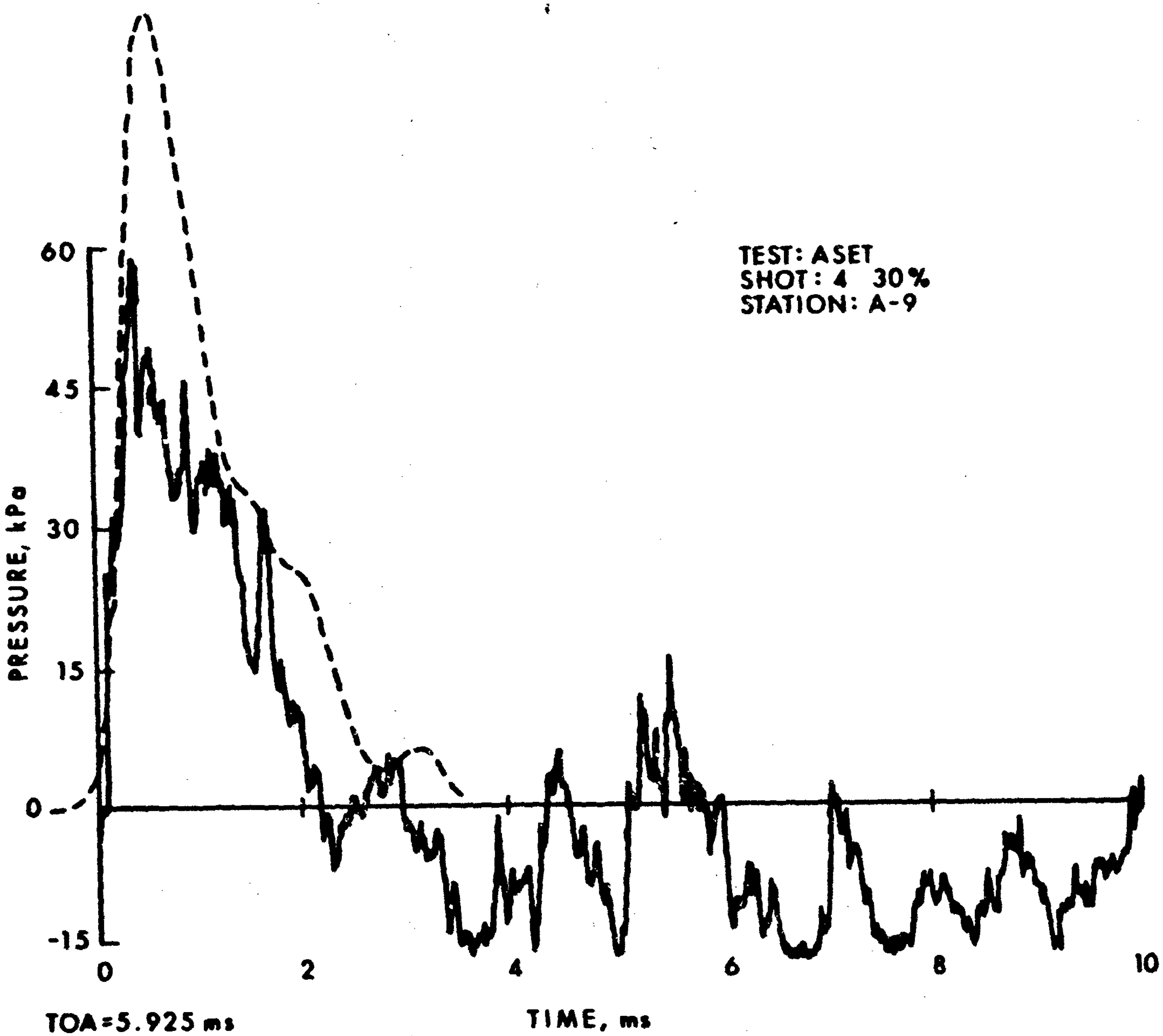

Figure 31. Comparison of measured and HULL predicted overpressure at gauge position 8.

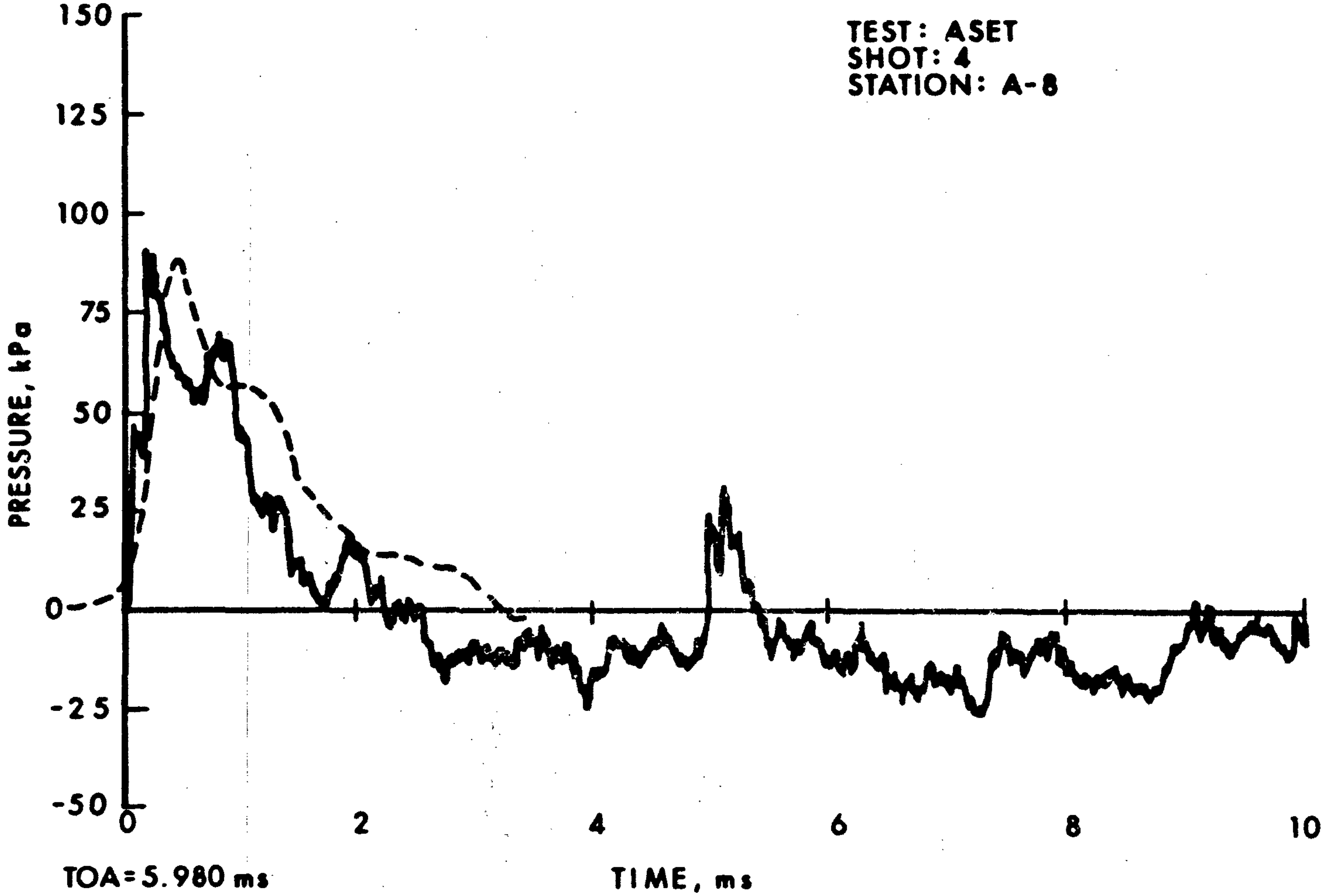

Figure 4j. Comparison of measured and HULL predicted overpressure at gauge position 9.

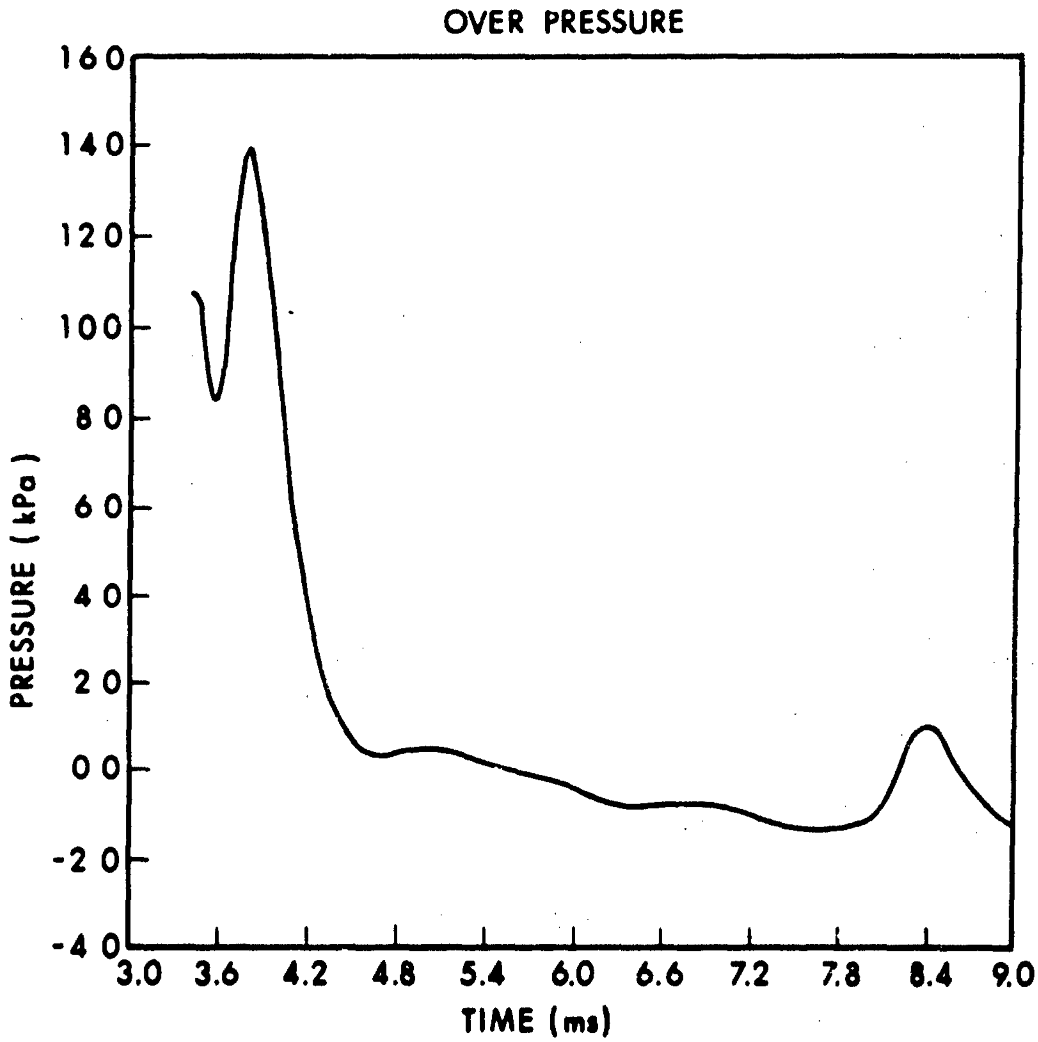

Figure 5a. Predicted HULL overpressure in a cell just in front of the open door of the model.

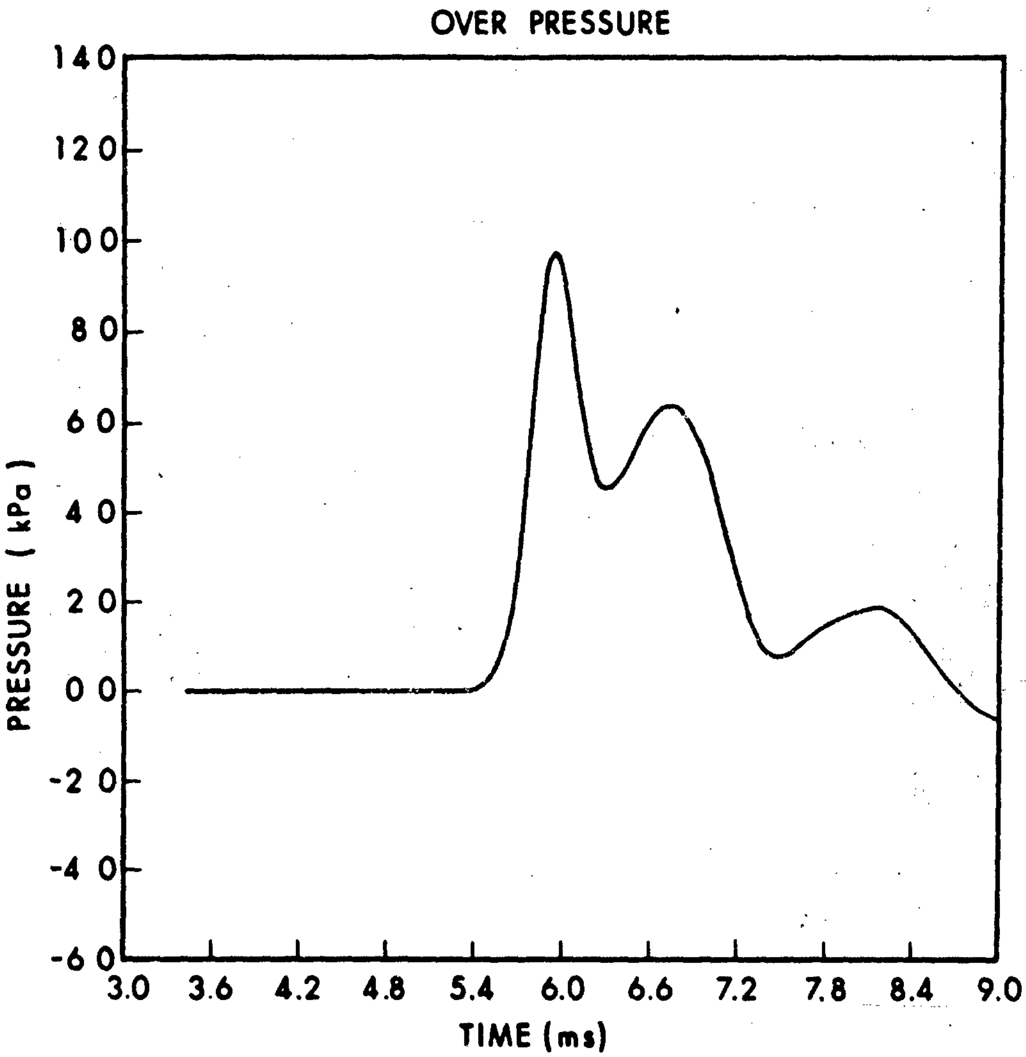

Figure 5b. Predicted HULL overpressure in the back corner of the model.

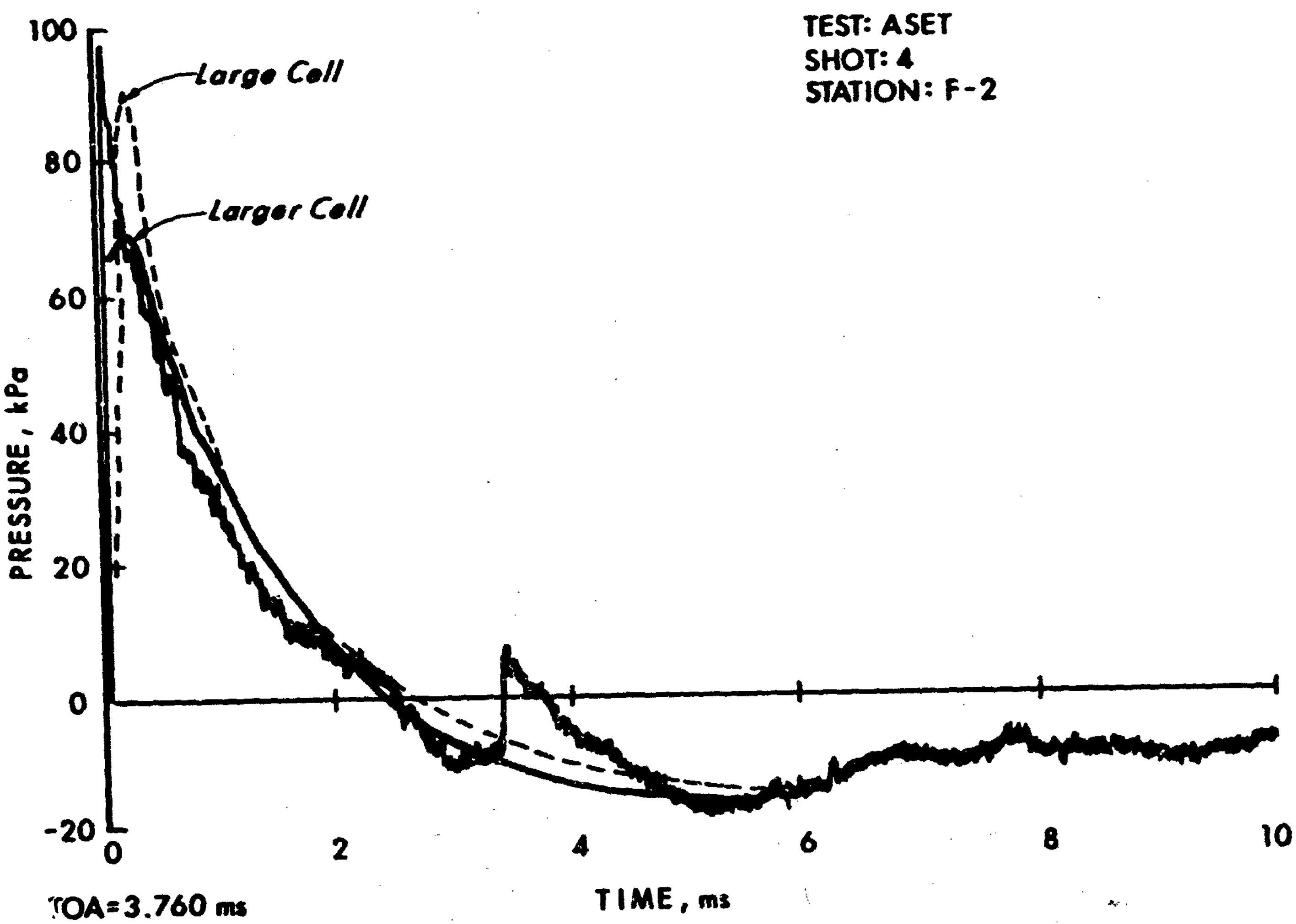

Figure 6. Comparison of measured free field overpressure 289 cm from ground zero and HULL predicted overpressure in two cells containing points at that distance but of different size and shape.

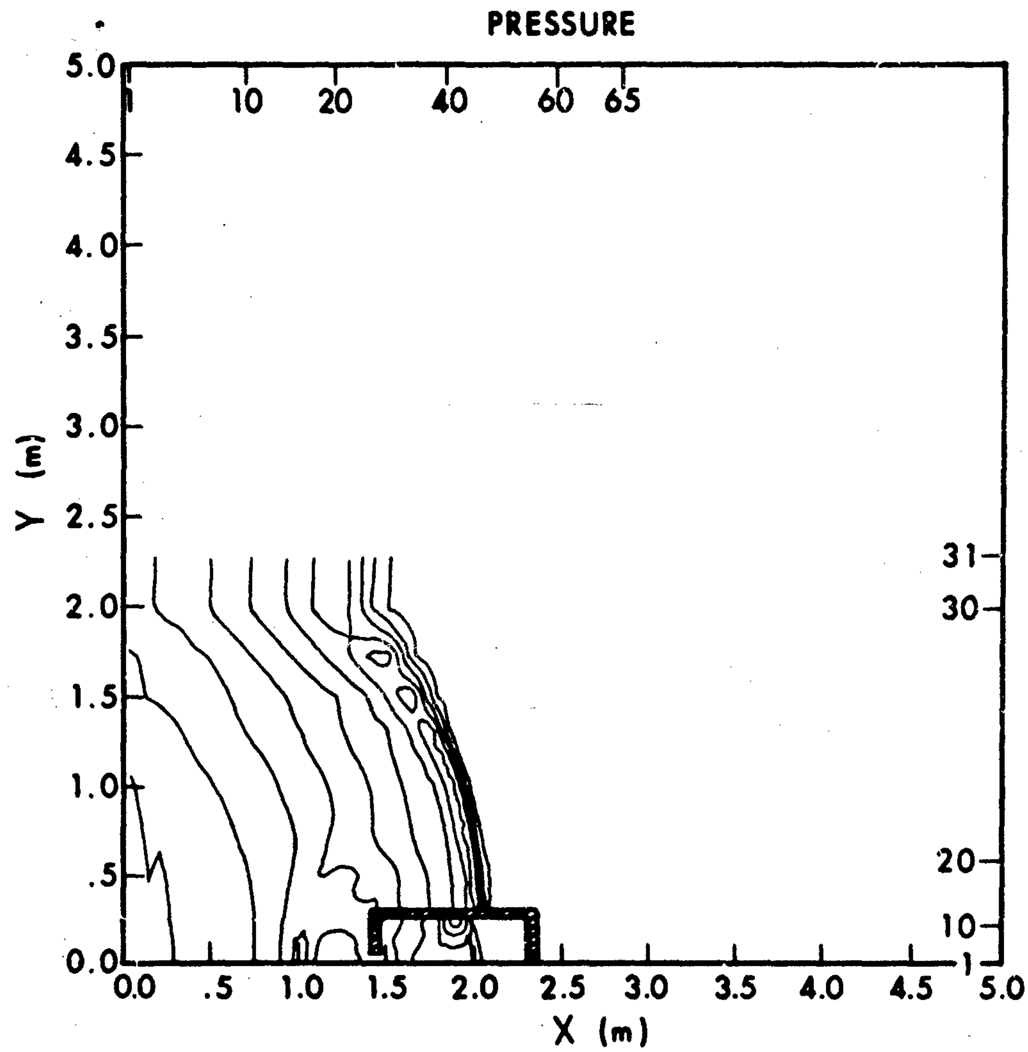

Figure 7. HULL generated isobars in the bottom computational plane at 5 ms.

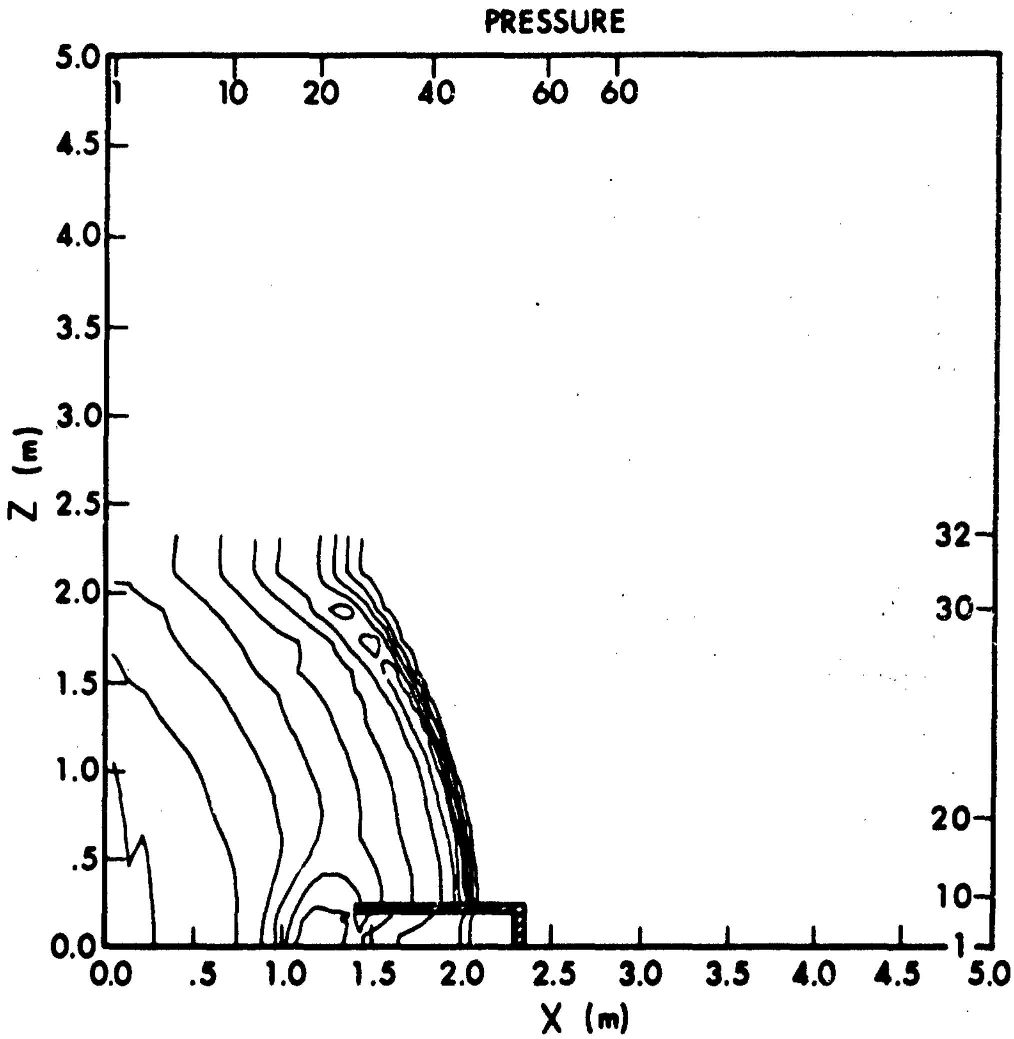

Figure 8. HULL generated isobars in the vertical plane adjacent to the y=0 symmetry boundary.

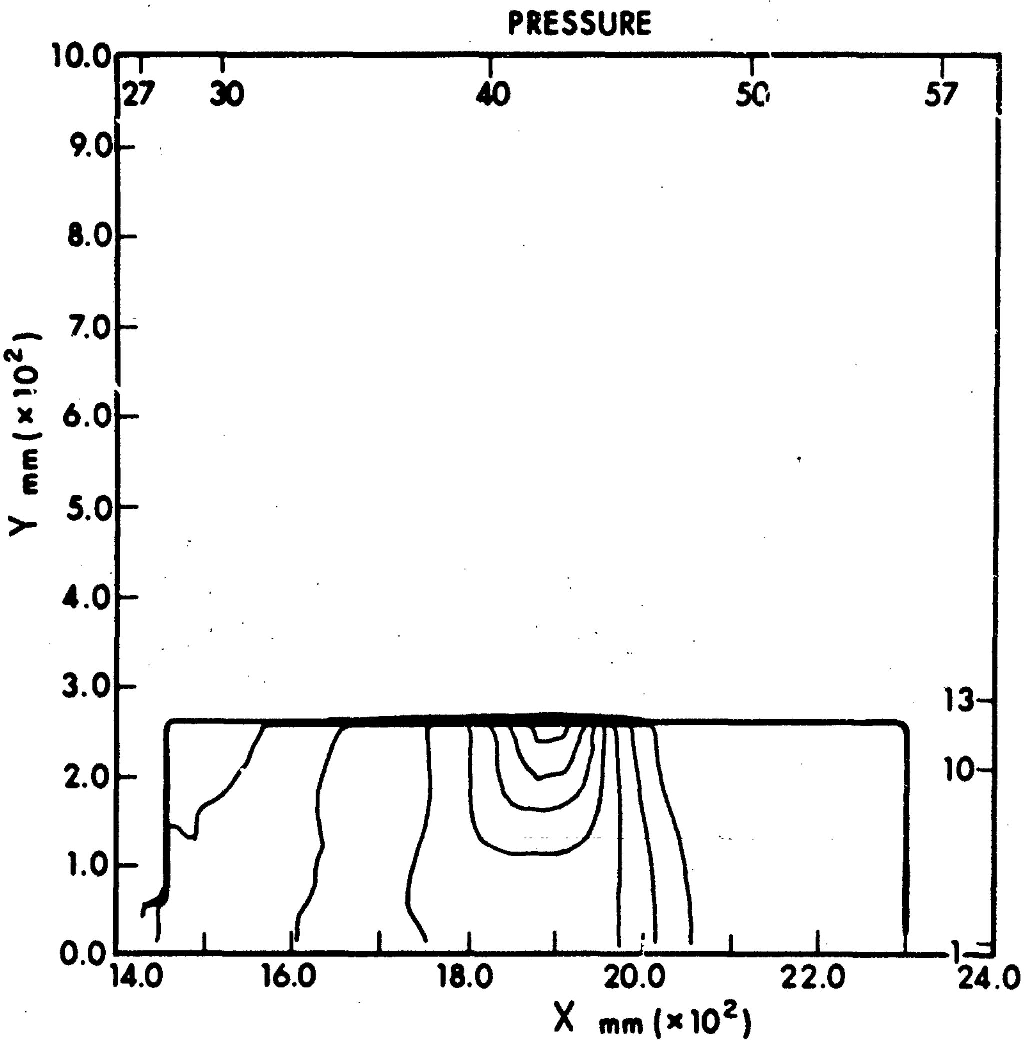

Figure 9a. HULL generated isobars near the floor of the model at 5 ms.

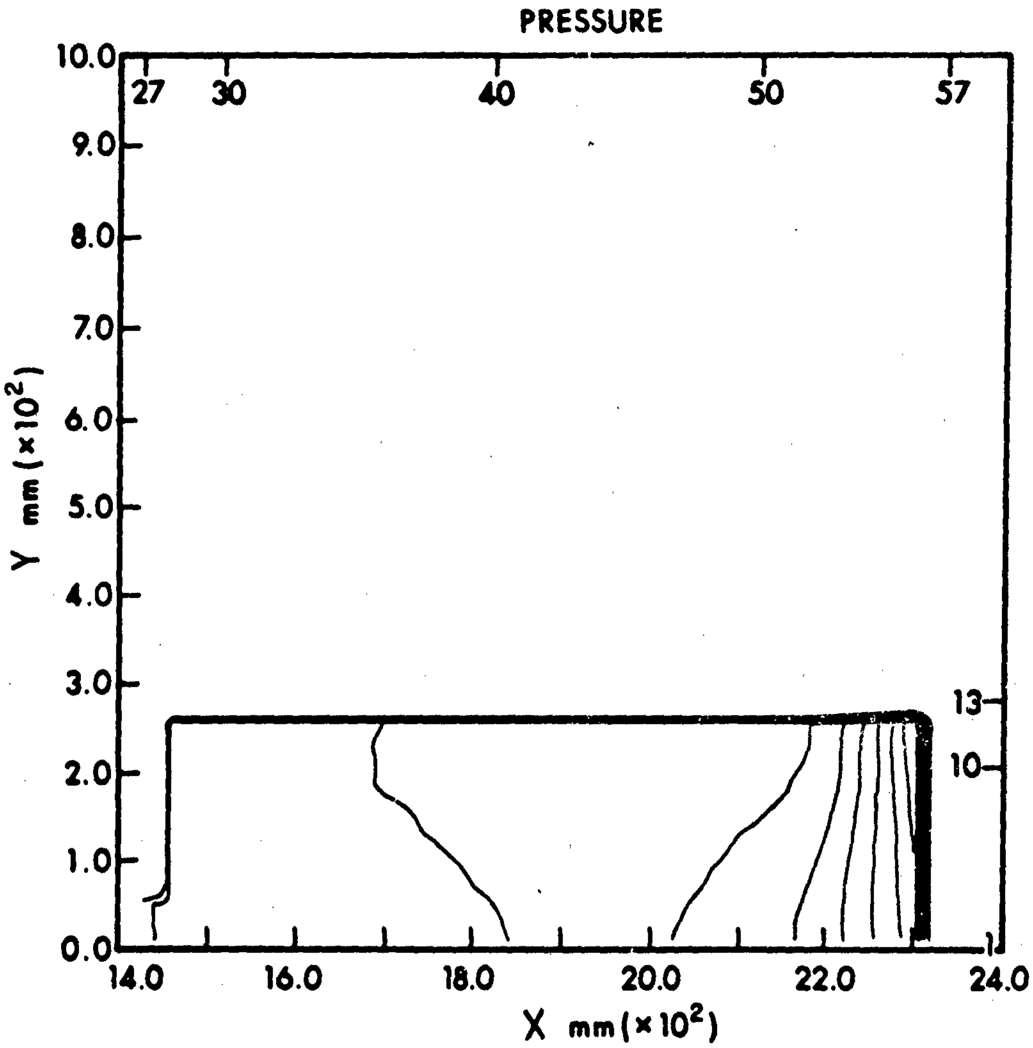

Figure 9b. HULL generated isobars near the floor of the model at 6 ms.

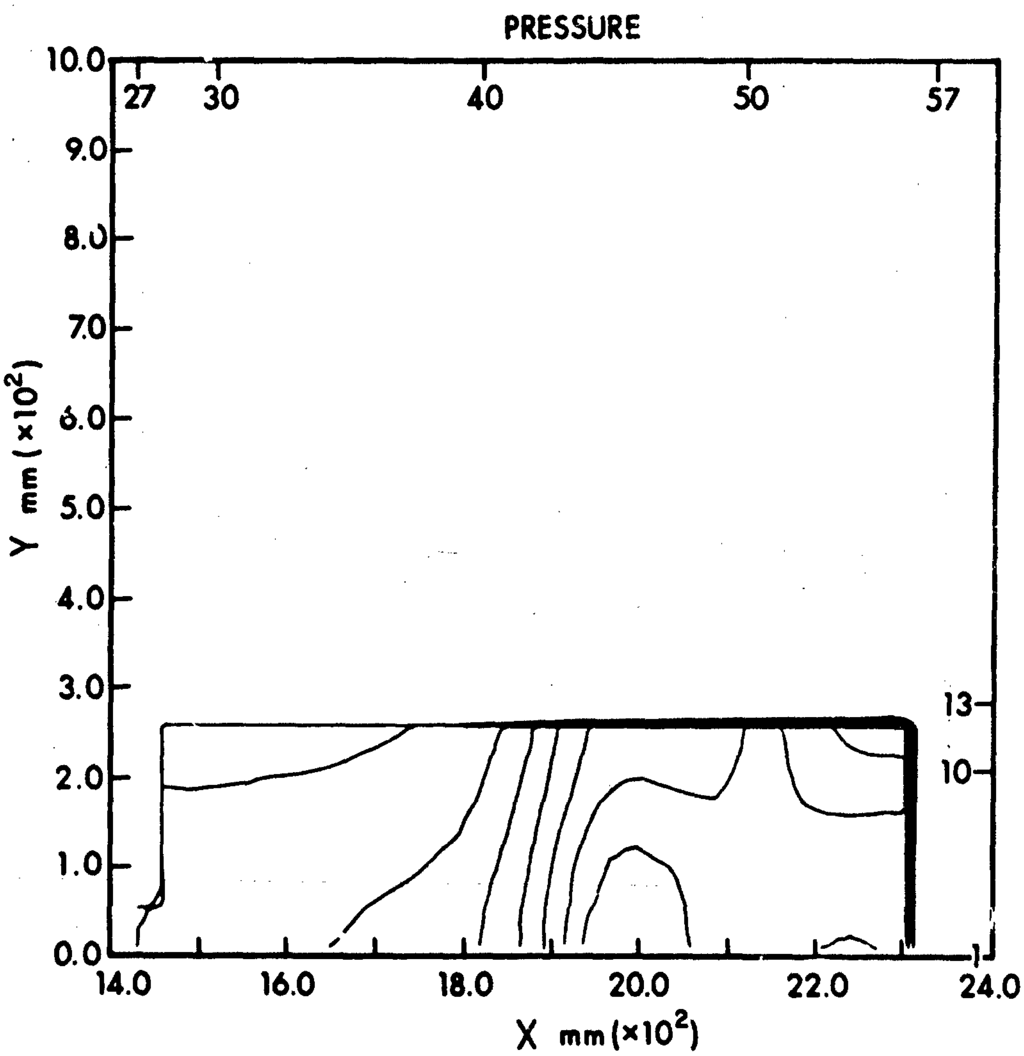

Figure 9c. HULL generated isobars near the floor of the model at 7 ms.

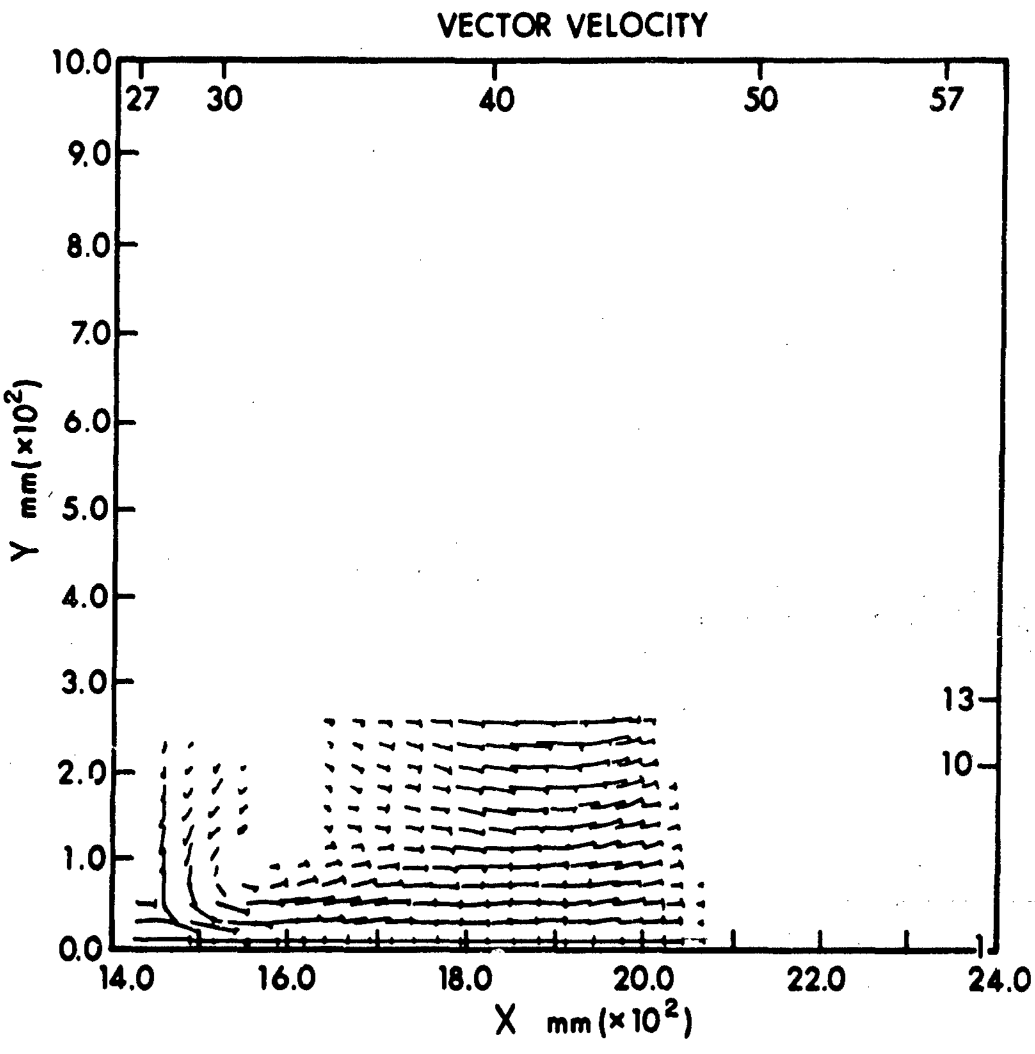

Figure 10a. HULL generated velocity vector plots near the floor of the model at 5 ms.

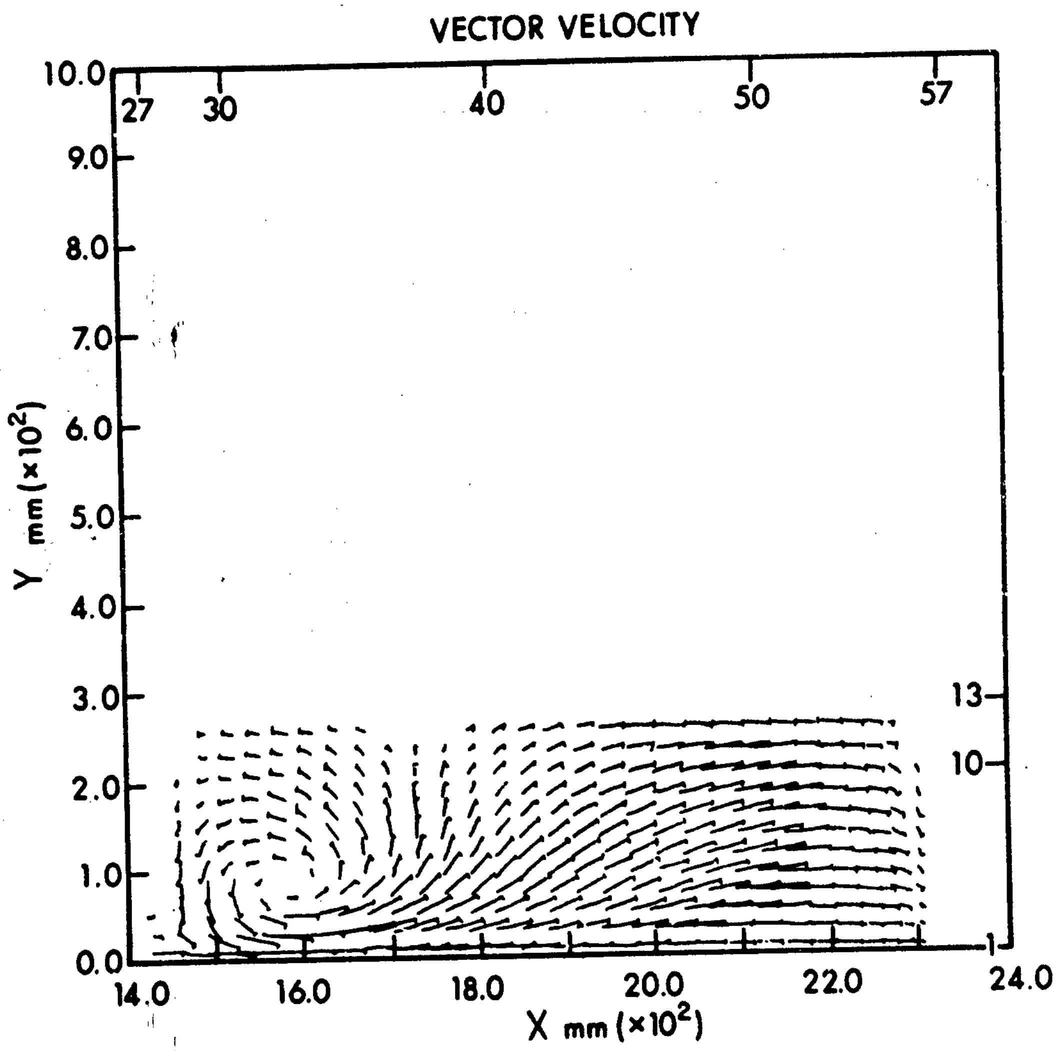

Figure 10b. HULL generated velocity vector plots near the floor of the model at 6 ms.

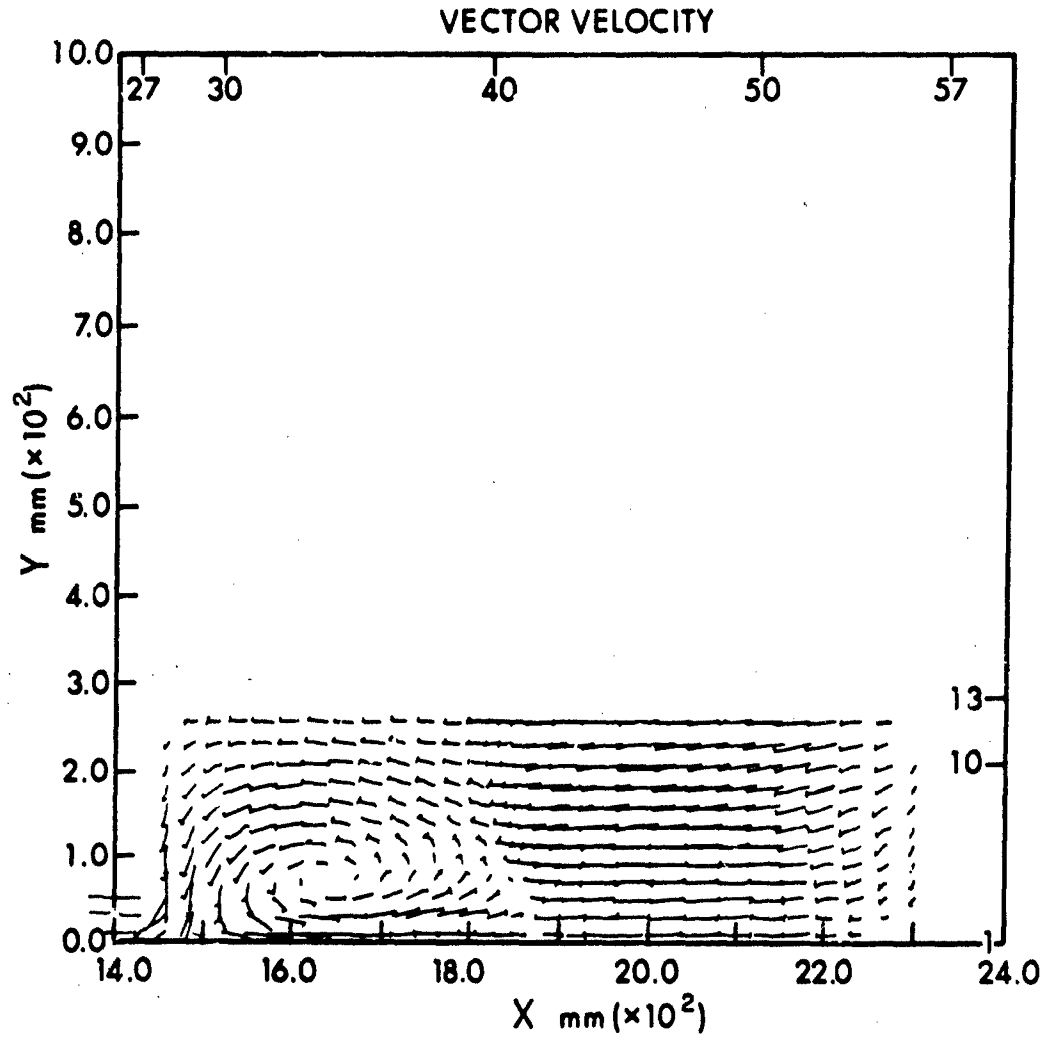

Figure 10c. HULL generated velocity vector plots near the floor of the model at 7 ms.

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